Direct photon measurements at RHIC-PHENIX

K.Okada for the PHENIX collaboration
RIKEN BNL Research Center, BNL Bldg.510A Upton, NY 11973, USA

Recent progress in direct photon measurements at RHIC-PHENIX detector is presented. In $p+p$ collisions, direct photons were measured in the transverse momentum range up to 25 GeV/c at $\sqrt{s} = 200$ GeV at mid-rapidity, extending the range beyond previous measurements. Next-to-leading order perturbative QCD calculations give a good description of the spectrum. It also provides a reference for the heavy ion collisions. A new virtual photon measurement in d+Au collisions indicates no or little cold nuclear effects. In Au+Au collisions, an unexpectedly large positive elliptic flow was observed. It provides information about the formation process of the hot and dense media produced in heavy ion collisions.

Direct photons are defined as photons that do not originate from hadronic decays. Once produced, a photon emerges from the reaction with little disturbance since it only interacts electromagnetically. Hence the direct photon is a unique probe to look deeply into the interaction. The partonic hard interaction is the dominant source of direct photons with large transverse momentum, p_T. The production rate in heavy ion collisions is expected to be consistent with ones in $p+p$ collisions with the average nuclear thickness function unless there is a nuclear effect modifying the parton distribution function. The direct photon production is a good reference to evaluate the jet quenching effect. At low transverse momentum, there are several production mechanisms in heavy ion collisions. It can be produced from $q+\bar{q}$ annihilation in sQGP and from hadron annihilation in the hadronic phase. Also by the interaction with the medium, the parton bremsshtraulung and fragmentation process might be modified compared to the case of $p+p$ collisions.

Up to now, direct photon measurements at PHENIX have been performed with the central arm spectrometers. Real photons are detected in electromagnetic calorimeters (EMCal). Each of two EMCals covers 0.5π rad in azimuthal angle (ϕ) and $|\eta| < 0.35$ in pseudorapidity. The charged particle tracking was performed by the drift chambers and the pad chambers. The ring imaging Cherenkov counter (RICH) provides a powerful electron identification capability. For event classification, there are global detectors. The beam-beam counters (BBCs) positioned at pseudorapidities $3.1 < |\eta| < 3.9$ are used for the minimum bias trigger and for the determination of the centrality class and the reaction plane. The reaction plane detector (RXP) located at $1.0 < |\eta| < 2.8$ was installed for the 2007 data taking period. The PHENIX detector is described in detail elsewhere [1].

The p_T reach in the measurement of the direct photon production in $p+p$ collisions at $\sqrt{s} = 200$ GeV is up to 25 GeV/c. The NLO pQCD calculation shows a good agreement with the data. Figure 1 shows a collection of direct photon cross section measurements in $p+p$ and $p+\bar{p}$ collisions from various experiments. Except a couple of experiments, they are all on a universal curve as a function of $x_T = 2p_T/\sqrt{s}$ with a multiplication of $\sqrt{s}^{4.5}$ to the cross section for a wide range of collision energy. Surprisingly, the PHENIX measurements of low p_T points with virtual photon method [2,3] are also on the same curve.

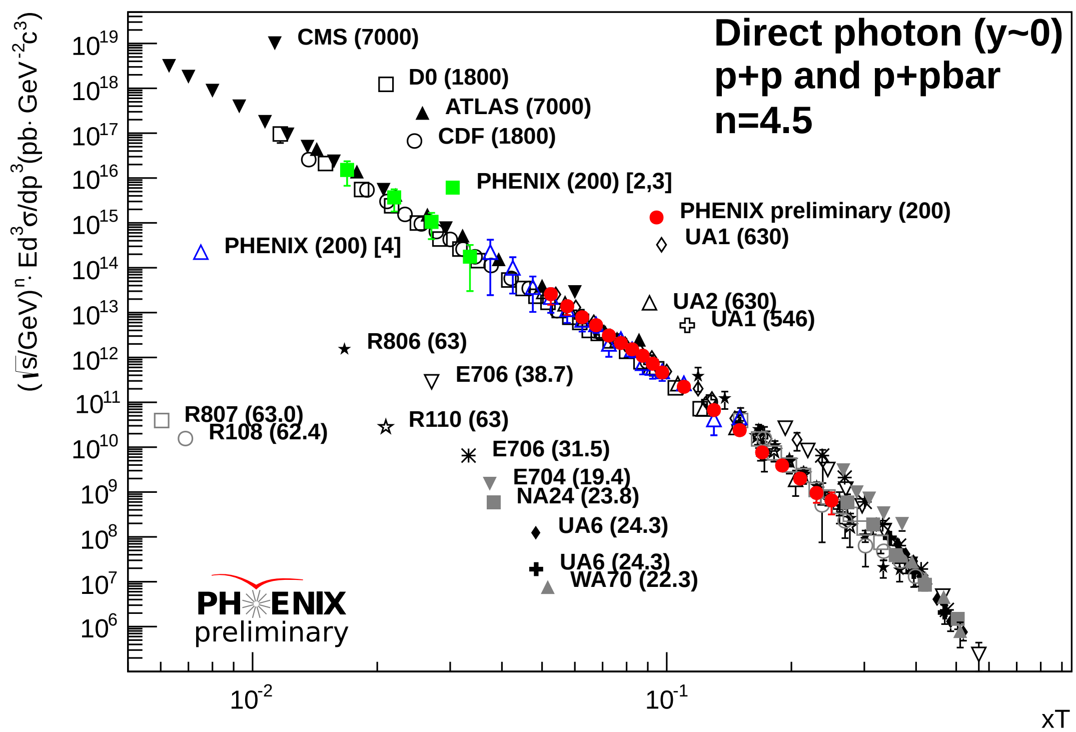

Figure 1: Various direct photon cross section measurements in $p+p$ and $p+\bar{p}$ collisions scaled by $\sqrt{s}^{4.5}$ on $x_T \equiv 2p_T/\sqrt{s}$. The legend shows the experiment and the center of mass energy [GeV] in parenthesis.

When the p_T goes high enough that the valence quark effect is dominant, we expect less direct photon production rate in heavy ion collisions than in the scaled $p+p$ collisions. It is because in a heavy ion d quark is dominant to u quark, while in the proton it is 1:2, and the rate is proportional to charge square in the $q+g$ scattering. The measurement of direct photon production in Au+Au collisions at $\sqrt{s} = 200$ GeV will be finalized soon.

As going to lower p_T ($p_T \lesssim 5$ GeV/c), experimentally it gets harder to extract the direct photon signal because of large background contribution of decay photons. Another way to access the direct photon is to measure the electron pair from its internal conversion. In this approach, the contribution of decay photons (mainly from π^0) is suppressed by applying a threshold on the pair invariant mass. However it requires a large integrated luminosity in compensation for the small conversion probability ($\sim 1\%$). We measured the direct photon production in $p+p$ and Au+Au at $\sqrt{s} = 200$ GeV with this virtual photon method [2,3]. In central Au+Au collisions, the excess of direct photon yield over $p+p$ is exponential in p_T. From the inverse slope, the average temperature was extracted. For the cold nuclear effect, direct photons in $d+$Au collisions are also measured (Fig. 2). The fact that they agree with scaled $p+p$ data indicates little or no nuclear effects. The spectrum provides an important information for the initial condition of the high energy heavy ion collisions.

The azimuthal anisotropy with respect to the reaction plane is an additional probe to explore the development of the medium. The lowest Fourier component that appears in the symmetric

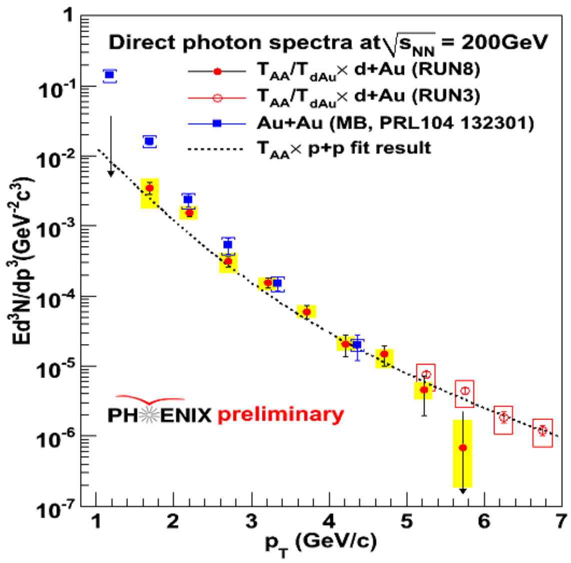

Figure 2: Direct photons in $d+\mathrm{Au}$ with the virtual photon method are scaled and compared with the data points in Au+Au collisions. Scaled $p+p$ fit result is also shown.

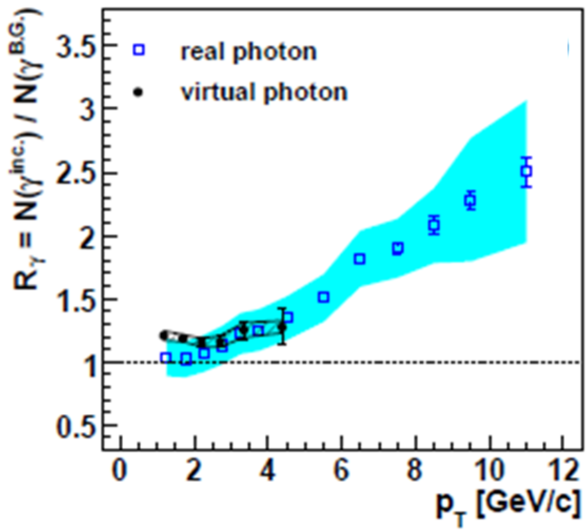

Figure 3: The direct photon excess ratio (R_γ) in Au+Au collisions. They are measured with virtual photons [2] (solid black circles) and real photons in the EMCal [5] (open blue squares).

geometry is the second term (called as ν_2 or elliptic flow). Eq. 1 shows the definition.

$$\frac{dN}{d(\phi - \Phi_{RP})} = N_0[1 + 2\nu_2 \cos 2(\phi - \Phi_{RP})], \tag{1}$$

where the azimuthal angle Φ_{RP} is defined by the reaction plane of the two nuclei. There are several approaches to measure the ν_2. Among them the simplest concept is to determine the Φ_{RP} with soft particles and to measure the particle production with respect to the Φ_{RP}. It is important to avoid or to correct the self correlation between the particle production ϕ and the reaction plane Φ_{RP}. At PHENIX, several global detectors were used to determine the Φ_{RP}. The resolution of Φ_{RP} was determined by the comparison of subsets in two side of the interaction point. It works as a dilution factor of the azimuthal dependence.

For the direct photon ν_2 (ν_2^{dir}), since we are not able to identify the direct photon event by event, we need to subtract the background components. The ν_2^{dir} is then obtained from the inclusive photon ν_2^{inc} and the background photon ν_2^{BG} as

$$\nu_2^{dir} = \frac{R_\gamma \nu_2^{inc} - \nu_2^{BG}}{R_\gamma - 1}, \tag{2}$$

where R_γ is a direct photon excess ratio defined by N^{inc}/N^{BG}. It depends on p_T as shown in Fig. 3. Both measurements with virtual photons and with real photons in the EMCal agree each other. At low p_T region ($p_T < 4$ GeV/c), the virtual photon method gives smaller systematic uncertainties and R_γ have non-zero values. The ν_2^{BG} is calculated from the measured ν_2 of π^0 ($\nu_2^{\pi^0}$). Other hadronic decay components are also derived from $\nu_2^{\pi^0}$.

Figure 4 shows the measurement of direct photon ν_2 for different centrality bins in Au+Au collisions at $\sqrt{s} = 200$ GeV [6]. At high p_T ($\gtrsim 5$ GeV/c), the ν_2^{dir} is consistent with zero, which is expected from hard scattering source. However a possible (small) elliptic flow cannot be rejected with the current uncertainties. At low p_T, the ν_2^{dir} is large, as much as the ones of hadrons [7]. In this region the size of ν_2^{dir} is sensitive to the formation time of the dense medium [8]. Larger ν_2^{dir} indicates later formation time. Currently as shown in Fig. 4 (d), the theoretical calculations are too small to the data.

The next step is to measure the ν_2^{dir} fully with electron pairs. It reduces the systematic uncertainties related to the π^0 background and the non photon contribution. However the yields go down by a factor of 200. Even in the lowest p_T region ($1 < p_T < 3$ GeV/c), it is a challenge with the current data sample. Note that there is an interesting suggestion about the enhancement of electron pair production in a strong magnetic field in heavy ion collisions[9]. If it is true, the assumption used to connect the yield of the electron pair to one of the direct photon needs to be revisited.

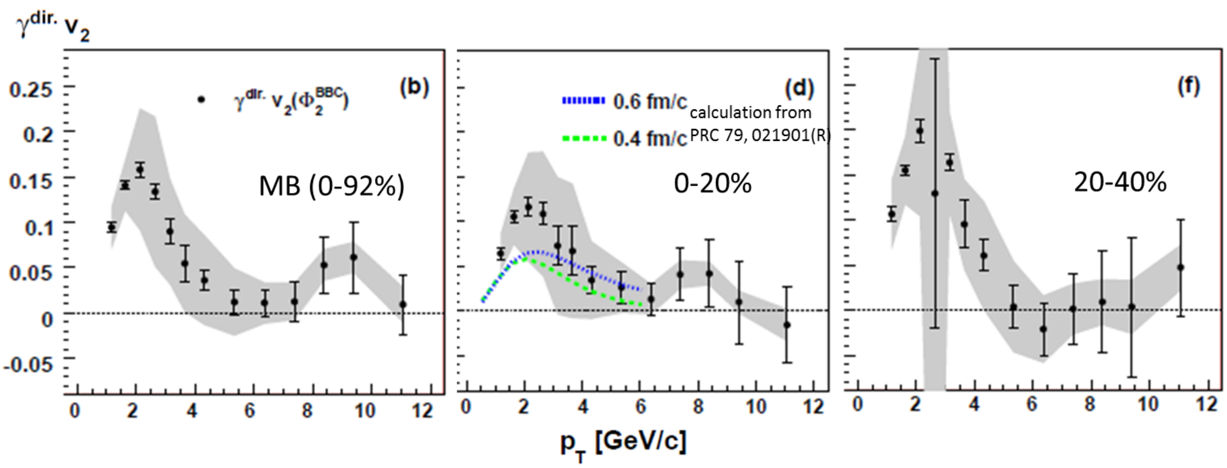

Figure 4: Direct photon ν_2^{dir} for different centrality classes[6]. In (d), theoretical calculations for different formation times are shown.

In summary, the PHENIX detector measured the direct photons over a wide p_T range at mid-rapidity in $p+p$, d+Au, and Au+Au collisions. The EMCal with high granularity were able to separate single photons from merged π^0 photons. In $p+p$ collisions, the direct photon spectrum was measured up to $p_T = 25$ GeV/c. The high rate capability of the data acquisition system and the excellent electron identification enabled us to access the direct photon production in the low p_T thermal production region via the virtual photon method.

We measured an unexpectedly large positive elliptic flow in the thermal production region. No theoretical explanation assuming the flow development in the QGP state exists yet.

For the future, the PHENIX collaboration plans to upgrade the detector. The immediate design is for the jet reconstruction, but its large acceptance will open new possibilities for the direct photon measurement. The physics cases of the upgrade detectors are measurements in large rapidity coverage, direct photon and jet correlation for the constraint of the kinematics, and a collection of a large statistics of electron pairs for virtual photon analysis.

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